Experimental Design Approach to Predicting Causal Interaction Between Radar and Commercial LTE Networks

Johanna Dwyer

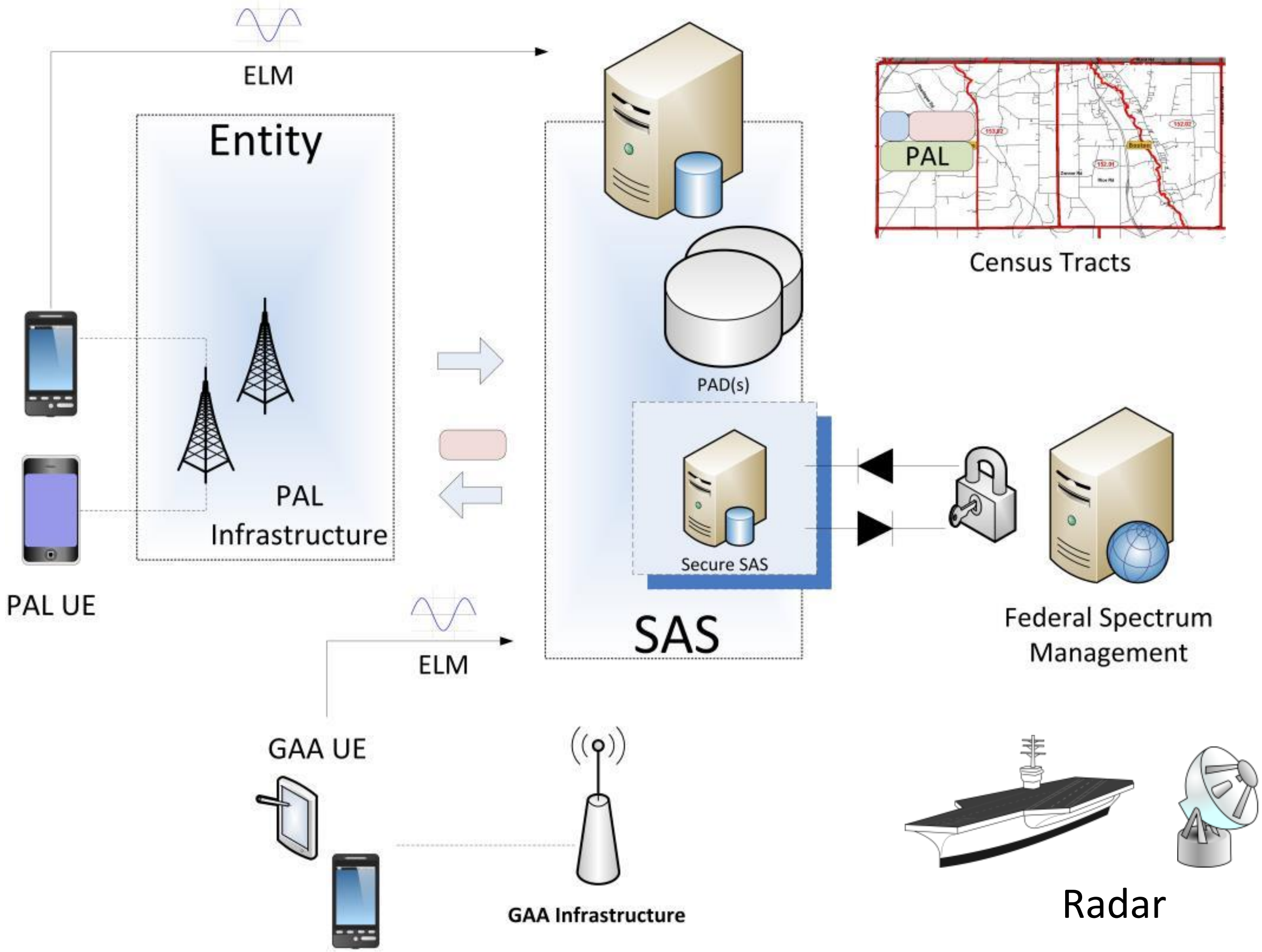
General Manager

Overview

- The Vision of Spectrum Sharing
- Traditional approaches to analyzing the interaction between Radar and LTE
- Motivation for new techniques
- Design of Experiments
- Methodology
- Limitations
- Implications

The Vision of Spectrum Sharing

- The FCC has proposed a Spectrum Access System (SAS) approach to spectrum sharing
- Incumbents register with legacy spectrum management databases, and LTE / public users register with the SAS
- Requests go through the SAS with secure interaction to legacy spectrum management
- Intelligent decisions on spectrum allocations requires a strong understanding of the Radar/LTE interaction



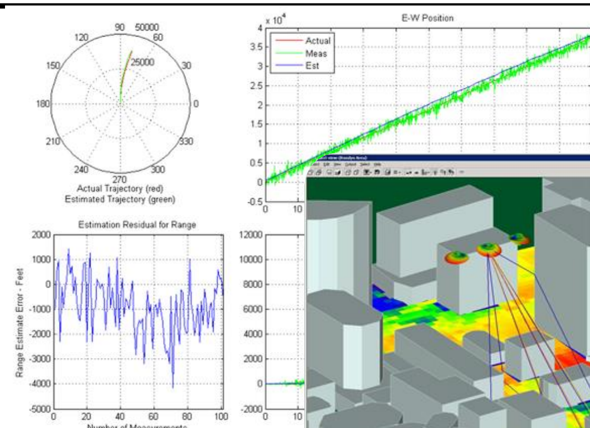
Traditional Approaches to Quantifying Interactions

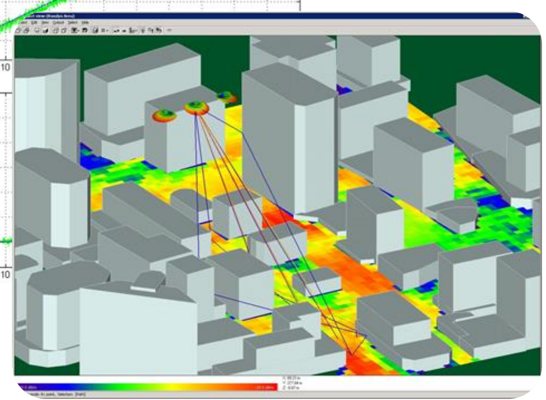
Analytical

$$\frac{P_{RX}}{P_{TX}} = \frac{\beta\lambda^2}{16\pi^2 d^4} \qquad \frac{\sigma N(T+1)}{P_{TX}} = \frac{\beta\lambda^2}{16\pi^2 d^4}$$

$$A \propto T^{-\frac{2}{\alpha}}$$

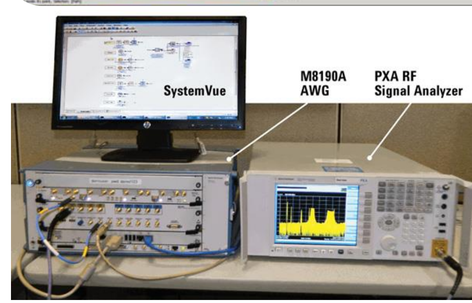
Simulation





Sources:
www.mathworks.com
www.remcom.com

Bench Test



Source: www.mwrf.com

Assumptions/Limitations

- Channel
- Noise Floor
- Path Loss
- Terrain
- Building DXF
- Cable loss
- Antenna height
- Exact location
- Multipath

The bench isn't real life.

Motivation for New Approaches

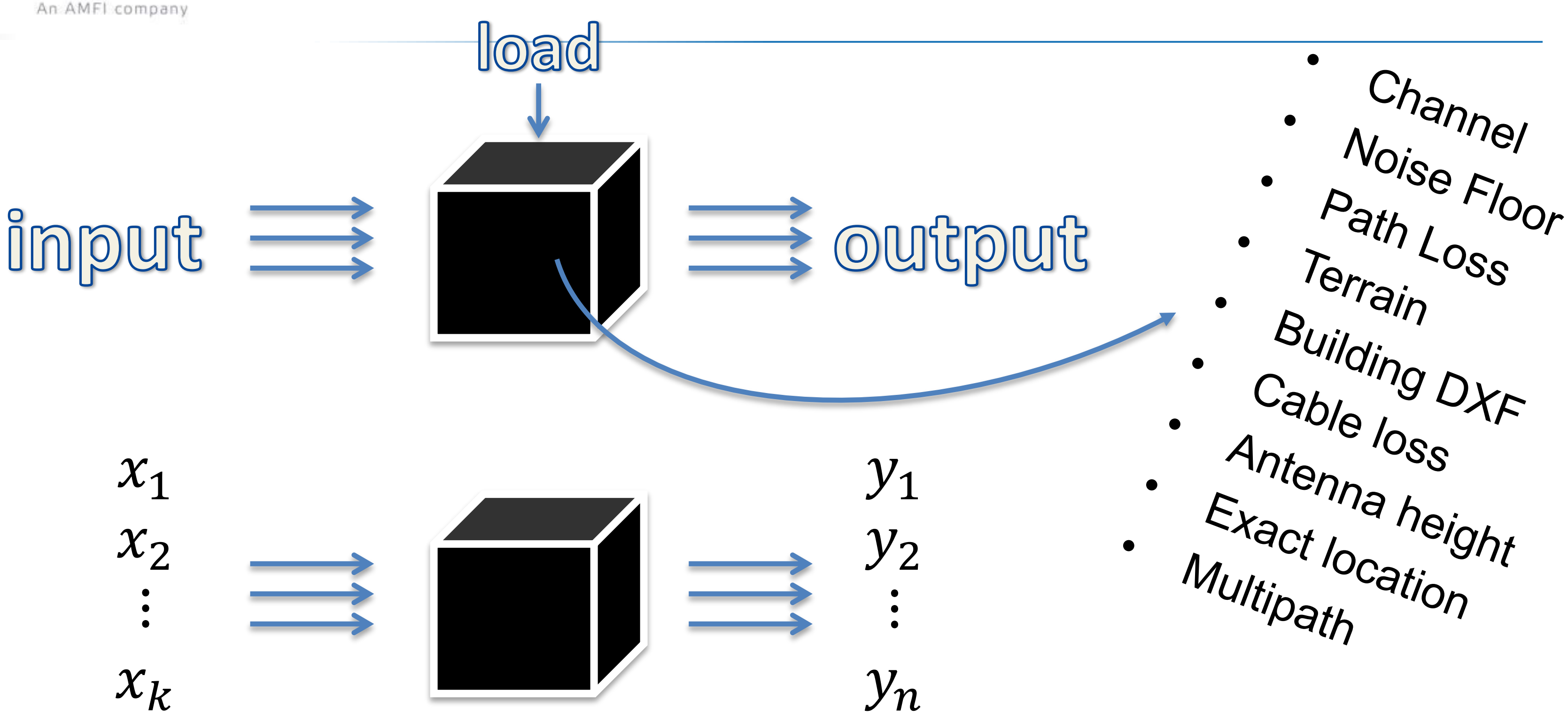
- It’s not enough to just calculate static exclusion zones. The exclusion zones need to adapt to the spectrum usage
- Radar operations can change based on mission needs
- The system needs the ability to predict how certain changes in radar operations will affect secondary users
- Current methods rely significantly on *a priori* knowledge of interference thresholds, configuration parameters, channel characteristics, terrain/building databases, and noise
- Small cell deployment in urban environments and indoor campus settings magnify the shortcomings
- It benefits everyone to leverage distributed and ‘crowd-sourced’ observables, reducing costs and increasing usability

“Real Life” testing is expensive. You had better have a good plan.

“Design of experiments (DOE) is a systematic, rigorous approach to engineering problem-solving that applies principles and techniques at the data collection stage so as to ensure the generation of valid, defensible, and supportable engineering conclusions. In addition, all of this is carried out under the constraint of a minimal expenditure of engineering runs, time, and money.”

-NIST/SEMATECH e-Handbook of Statistical Methods, 2012

The Beauty of the "Black Box" System Model



Define a **test** as the application of a repeatable load on the system where the inputs (*x's)* are set to a unique configuration and the outputs (*y's)* are measurable.

federated wireless™

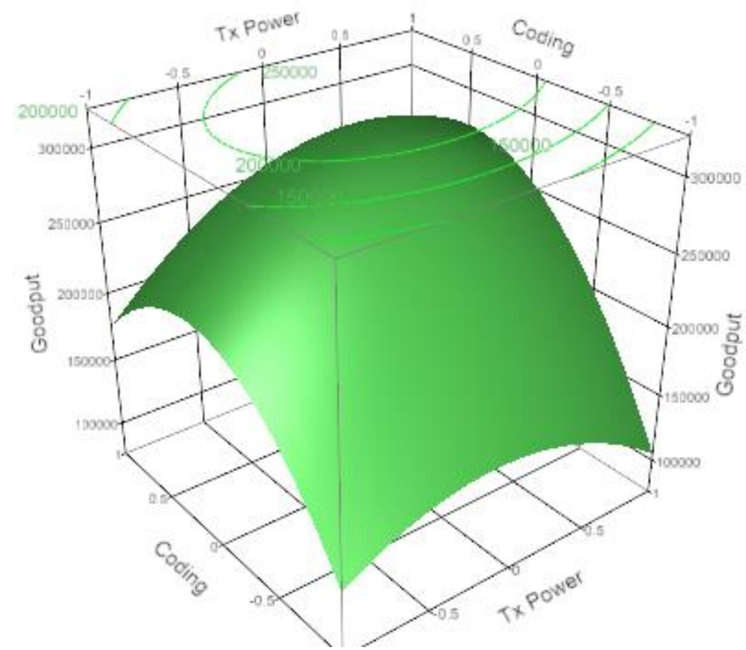
An AMFI company

The Goal

Perform a minimum number of tests to…

1. Identify which *inputs* are significant to the outputs
2. Identify which *interactions* of *inputs* are significant to the outputs
3. Quantify this statistically
4. Identify predictive models of the outputs of interest as functions of the inputs
5. Potentially use the models to identify the necessary inputs to achieve a desired goal (maximize, minimize, target) for a specific output.

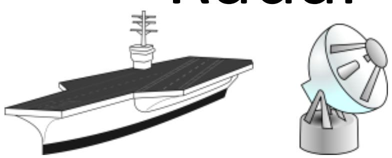
$$y_1 = f(x_1, x_2, \dots, x_k)$$
$$y_2 = f(x_1, x_2, \dots, x_k)$$
$$\vdots$$
$$y_n = f(x_1, x_2, \dots, x_k)$$



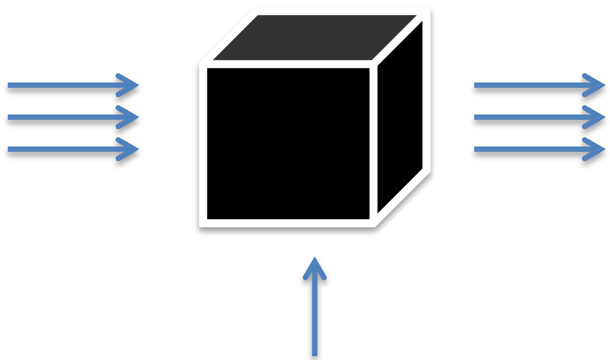
Source: A. Amanna, "Statistical Experimental Design Framework for Cognitive Radio," PhD Dissertation, Virginia Tech, May 2012.

Radar / LTE Interaction Model

Radar



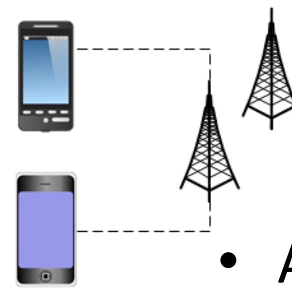
- Carrier frequency
- Pulse width
- Transmit power
- Receive power
- Repetition rate
- Rotation rate
- Duty cycle
- Location
- Mobile / Static
- Antenna
  - gain
  - pattern
  - aperture
  - angle



Example Repeatable Load

- Radar: perform target tracking
- LTE: Transfer a data file

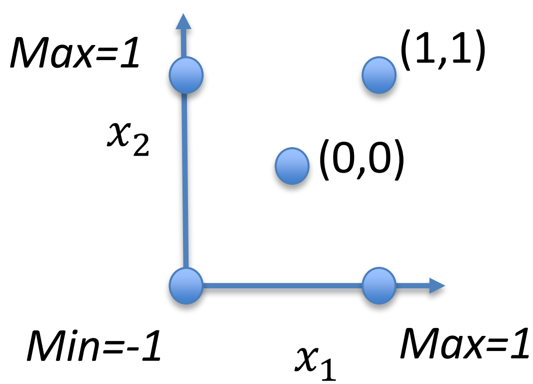
LTE



- Aggregate Throughput
- Goodput
- FER
- QoS
- QoE
- Dropped Calls
- KPIs
- MDT data

How Do You Vary the Inputs?

- Consider your inputs (x's) as a search space
- Bound the search space by the min/max of each *x*
- Normalize each *x* to a [-1,1] scale
- A basic set of tests would be the vertices of the search space
  - Known as the Factorial Design
  - There are 2^k unique configuration combinations of *x's*
  - (0,0) is the center of search space



A simple test plan:

Test	x_1	x_2	y_1	y_2	y_3
1	-1	-1			
2	1	-1			
3	-1	1			
4	1	1			
5	0	0			

How Do You Get the Model for the Outputs?

- Use least squares estimation methods to develop models
- Assume models take a form of: $\mathbf{y} = \mathbf{X\beta} + \boldsymbol{\epsilon}$
- Use test design and collected data to populate matrix

$$\mathbf{y} = \begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_n \end{bmatrix} \quad \mathbf{X} = \begin{bmatrix} 1 & x_{11} & x_{12} & \dots & x_{1m} \\ 1 & x_{21} & x_{22} & \dots & x_{2m} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ 1 & x_{n1} & x_{n2} & \dots & x_{nm} \end{bmatrix} \quad \boldsymbol{\beta} = \begin{bmatrix} \beta_0 \\ \beta_1 \\ \vdots \\ \beta_m \end{bmatrix} \quad \boldsymbol{\epsilon} = \begin{bmatrix} \epsilon_1 \\ \epsilon_2 \\ \vdots \\ \epsilon_n \end{bmatrix}$$

- Solve for estimation of coefficients

$$\widehat{\boldsymbol{\beta}} = (\mathbf{X}'\mathbf{X})^{-1}\mathbf{X}'\mathbf{y}$$

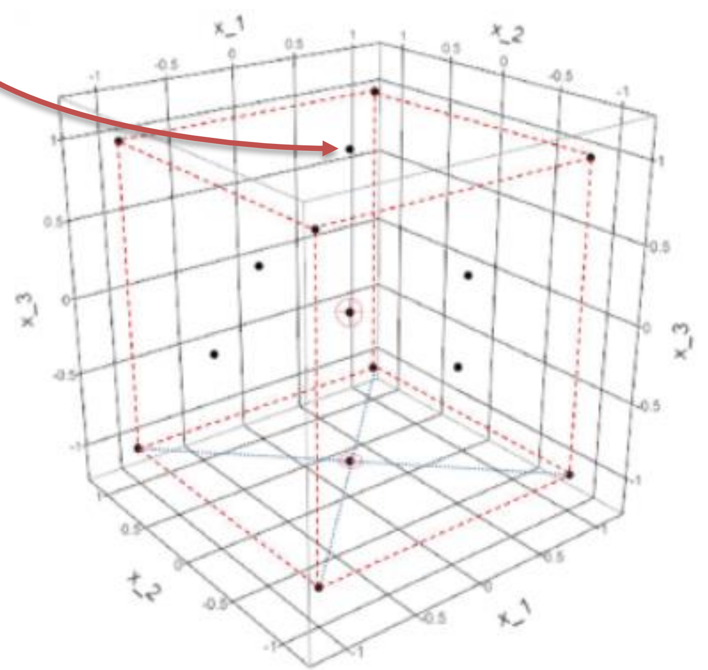
- Rewrite into model for each output metric

$$y = \beta_0 + \sum_{i-1}^{m} \beta_i x_i + \sum_{i-1}^{m} \beta_{ii} x_i^2 + \sum_{i-1}^{m-1} \sum_{j-i+1}^{m} \beta_{ij} x_i x_j$$

The Tradeoff: Knowledge vs. Cost in Terms of Number of Tests

Type	Cost	Benefit
Factorial	Lower (2^k) Vertices	Good for screening Model is linear
Response surface methodology	Add in tests at nominal points	Polynomial model shows curvature

Test	Box-Behnken			Central Composite Design		
	x_1	x_2	x_3	x_1	x_2	x_3
1	-1	-1	0	-1	-1	-1
2	-1	1	0	-1	-1	1
3	1	-1	0	-1	1	-1
4	1	1	0	-1	1	1
5	0	-1	-1	1	-1	-1
6	0	-1	1	1	-1	1
7	0	1	-1	1	1	-1
8	0	1	1	1	1	1
9	-1	0	-1	-1	0	0
10	1	0	-1	1	0	0
11	-1	0	1	0	-1	0
12	1	0	1	0	1	0
13	0	0	0	0	0	-1
14				0	0	1
15				0	0	0



Limitations / Assumptions

"All models are bad; some are useful."

– George Box

- Assumes statistical error is normally distributed
- Some environmental factors are out of your control
  - Some *blocking* techniques exist to mitigate this
- The derived models are specific to the environment under which the data was collected; the methodologies extend to other situations but specific models may not
- Data collection is hard no matter how efficient a test matrix you have
- This approach is designed for continuous parameters. Discrete *x's* require mapping to the [-1,1] scale, which can be difficult
- Models may require translation from the normalized scale to natural units

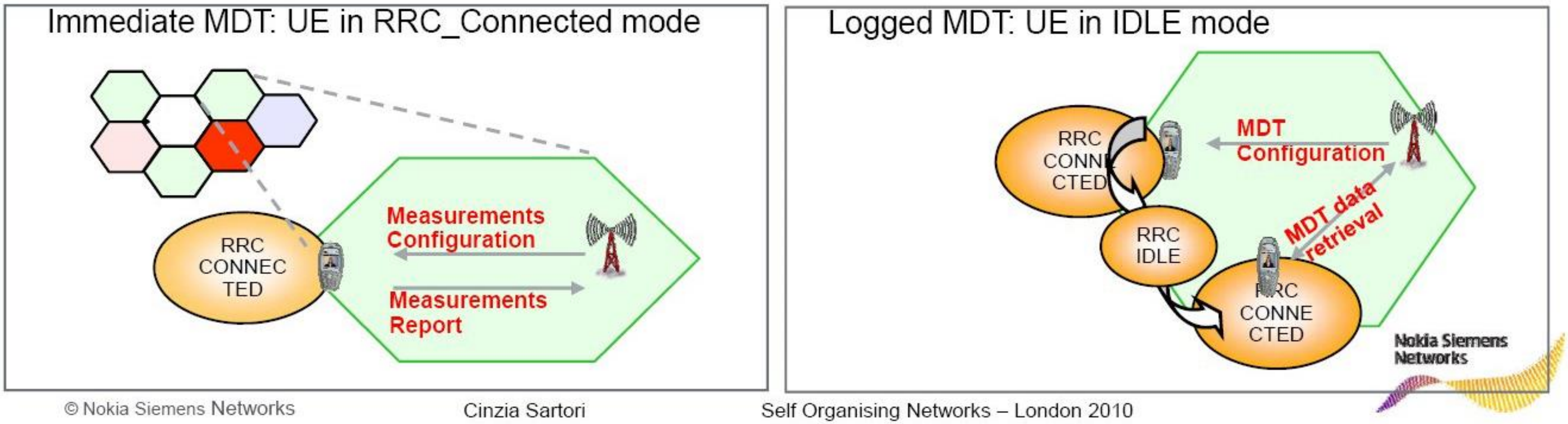
Applying DOE to Radar/LTE Interaction

- It is unrealistic to perform testing on a large number of input variables
- Domain knowledge is required to:
  - Initially filter out the most important input parameters to consider
  - Map the max/min boundaries of parameters
  - Define the repeatable load and measurable metrics
- Begin initially with running the simpler factorial tests
  - Identify the most significant parameters
  - Drop insignificant parameters from further consideration
- Expand testing to RSM test plans for higher resolution models

Potential Cellular Network Output Metrics

KPI Class	KPI	Description
Accessibility	Initial E-RAB establishment success rate	The Evolved Radio Access Bearer (E-RAB) provides the accessibility for the UE to the LTE network. The initial E-RAB establishment is included in the initial UE context setup procedure
	Added E-RAB establishment success rate	Once an E-RAB is added during the context setup, the E-RAB setup procedure provides counters for this metric
	RRC Connection Establishment Success rate	Describes the ratio of all successful RRC establishments to RRC establishment attempts for UTRAN network, and is used to evaluate UTRAN and RNC or cell admission capacity for UE and/or system load
	UTRAN Service Access Success Rate	Describes the ratio of all successful UTRAN access to UTRAN access attempts for UTRAN network
Retainability	E-RAB retainability	Retainability takes into account interruptions to service caused by releases initiated by the MME.
Integrity	Downlink Latency Downlink Throughput Uplink Throughput Downlink Packet Error Loss Rate Uplink Packet Error Loss Rate	
Mobility	Mobility Success rate	Takes into account preparation of target cell resources and the move from a source cell to a target cell
Availability	Cell Availability	This quantifies the length of time in seconds that a cell is available for service

Minimize Drive Test (MDT) Metrics



Source: 3G4Gblogspot.com

Metrics Include:

- UE measured reference signal received power (RSRP) and reference signal received quality (RSRQ)
- Received interference power
- Uplink/downlink rates
- Radio link failures
- Handover failures
- RF fingerprint using neighbor cell measurements

Implications

- Use of Design of Experiment techniques minimizes the need for additional sensing infrastructure by leveraging existing metric collection from commercial sector equipment
- These measurements provide ‘ground truth’ of the cause-effect relationship between heterogeneous users
- Compliments analytical and simulation-based predictive models
- Provides a deployment tool for placement of small-cells in urban environments and localized indoor networks
- Facilitates the paradigm shift from exclusion zones to performance-driven allowable zones
- Enables the Spectrum Access System to more efficiently manage the spectrum resource by knowing where and how mission changes will affect secondary users